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Proposing A Cyber-Physical Production Systems Framework Linking Factory Planning And Factory Operation

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Abstract

The challenges for industrial companies in the area of factory planning and operation are characterised on the one hand by permanently shortening product life cycles and increasing product diversity. Furthermore, the demand for ecologically sustainable processes is growing and the complexity of production systems is increasing due to higher product complexity. This results in a complex decision-making space for companies within factory planning and factory operation which is difficult to plan. The advancing digitalisation can bring a great opportunity here. Modelling and simulation can create greater transparency in the context of planning and operation, and processes can be designed to be ecologically sustainable and efficient. Currently, research approaches in the context of factory planning and operation are focussing on the application and use of digital methods and tools of the Digital Factory (DF). However, the application is limited to individual areas in factory planning or factory operation.

For this reason, this paper focuses on the design of a framework that addresses both factory planning and factory operation aspects and links them through modelling and simulation. Cyber-physical production systems (CPPS) can help here by mapping the individual modules within planning and operation using individual agents in agent-based simulation (AB). By linking planning and real data, the processes from planning and operation can be taken into account. From this, insights gained from planning can be simulated in an early phase and subjected to optimisation during operation. The cycle-oriented CPPS can be used on an ongoing basis by preparing the generic building blocks on the planning and operational sides through structured data acquisition and implementing them in the real world with the help of decision support from the virtual world.

Keywords

Factory Planning; Factory Operation; Cyber-Physical Production System, Agent-Based Simulation, Framework

1. Introduction

Shorter product life cycles, volatile market conditions, customer demands for individualized products and increasingly stringent environmental regulations in conjunction with growing scarcity of energy and resources are contributing to a turbulent environment with which companies are confronted [1]. The configuration of value chains in factories is additionally subject to an immensely increased complexity of planning tasks. Dynamic and cooperative value networks result in a frequent change of production requirements, which necessitates both an increased planning speed and an increased planning frequency of the production systems [2], [3]. Factory planning and factory operation face these challenges with a targeted, ongoing adaptation of production systems using methods and tools of digitalization, Industry 4.0 and Digital

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Factory (DF). Of great importance in this context are modeling and simulation for decision support in the planning and operating processes of new (greenfield) and rescheduled (brownfield) factories [2], [4]. However, it should be noted that the use of simulation technology often requires expert knowledge and is associated with high time and financial expenditure, which is why such applications are often still limited in companies despite the enormous potential benefits [5]. As a result, manufacturing companies are always faced with the dilemma of potentially reducing planning times on the one hand and the time and financial effort required to create sufficiently accurate simulation models on the other. In addition, the successful and efficient implementation of simulation projects requires a very good and up-to-date data and models representing the current state of production, both are often not yet available [6], [7]. The aspect of the transfer and reuse of models beyond the respective application context also takes on an important role. At the moment, there is still a need for action in industry and research and thus potential for optimization in the process-related, organizational and structural interface between factory planning and factory operation [8].

While a large number of approaches and frameworks exist in the context of production system modeling and holistic factory modeling, a framework for the coupling of planning and operation through the transfer of simulation models for production systems is not yet available in the literature. In particular, the procedure for initializing the models on the basis of planning data and the subsequent extension to the use of real data and thus a real representation of the production system is a central challenge for today's companies. In this context, the data basis should ensure a high degree of topicality, availability as well as quality, so that the input for simulation models is promising. In the area of modeling and simulation, the design of generic, adaptive building blocks (e.g. agent-based simulation (AB)) is a central aspect for the holistic use of simulation models.

In order to support the continuous development up to the further use of the simulation models, a Cyber-physical production systems (CPPS) approach from factory planning to operation is necessary. In the following, a framework is described that, starting from greenfield planning projects, supports the continuous development of simulation models up to operation into a tool that can be used for planning and operation. The cycle of the CPPS is particularly suitable in this framework, since in the later course brownfield changes in the production system follow a recurring cycle. Based on this approach, planners and operators are able to work in a common simulation model and implement changes in the production system in a common network. From this, findings from the planning can be transferred to the operation, but in addition, feedback from the operation to the planning is possible. All in all, the two areas are more closely networked and work more closely together, from which enormous potential can be leveraged.

2. Theoretical Background

2.1 Interface of factory planning to factory operation

In general, the factory is described as a place of corporate value creation and represents a complex system of various elements, such as products, machines and people, and their interrelationships. The relations of the elements to each other can be characterized on a material, informational, energetic, personnel, economic, spatial and temporal level. In addition, the overall system of the factory consists of several subsystems, which are distinguished from each other by a defined system boundary (e.g., production, logistics, etc.). The factory is the subject and object of factory planning and factory operation. [9], [10], [11]

Starting from factory planning, the organizational, process-related and structural design or adaptation of the production system takes place. In the literature, approaches are mainly found which are based on a systematic, goal-oriented and phase-specific planning procedure which builds on each other and links the various planning tasks (e.g., process, resource, structural planning, production operation and control, etc.). Due to the high complexity of factory planning projects, the planning phases are carried out with the involvement of a large number of players from a wide range of specialist areas. In this process, planning always proceeds from the rough to the fine and from the ideal to the real. Of particular importance is the parallelism of the planning phases, i.e., a subsequent phase can already be started when the previous phase has not yet been completed. Basically, the phases can be divided into preparation, structural, detailed, execution planning and execution, GRUNDIG gives a comprehensive overview of existing approaches as well as their differences [12]. In addition to new planning (greenfield), i.e., the completely new construction of a factory from scratch, and the re-planning (brownfield) of an existing factory, there are further planning cases within the life cycle consideration of a factory and its elements in the form of deconstruction and revitalization. Starting from the network and site level, the following levels become more and more detailed, up to the focus on the granular, detailed workplace of a specific area of a factory. The design of the production system, more precisely the arrangement of the production elements, is done taking into account appropriate flow systems. Factory planning involves permanent adaptation in the event of changes in the planning of the factory and factory operations. [9], [10], [11], [12], [13]

In contrast to factory planning, factory operation includes the structuring of the tasks of operating, directing and controlling the processes (including maintenance and service) in the factory. Here, production planning and control, manufacturing, assembly, storage, transport, quality and resource management are particularly important. In this way, the company's objectives are to be safeguarded by a socially, economically and ecologically (resource) efficient organizational structure and process organization in the participatory, transparent interaction of all factory elements. Of particular importance here is also the integration or regulation of the interaction of production, logistics and support processes. The overriding goal of factory operations can therefore be described as the efficient design of a factory's operations and its adaptation to necessary changes, with the creation of value added being a central element of factory operations theory. More precisely, the shortening of the start-up period as well as the operational and continuous improvement of serial production are aimed at. [10], [13], [14], [15]

In total, there are close mutual relationships between the two areas of factory planning and factory operation. Factory operation is strongly influenced by the framework conditions created by factory planning, but this also applies retrospectively, so that findings from factory operation must be reported back to factory planning. A corresponding bidirectional exchange between the two areas leads to an optimization of factory operations, in that adjustments can be made and future planning projects can be improved based on the information fed back. Optimally, factory planning thinks ahead of value creation and provides framework conditions for efficient and error-free processes. The processes, systems, and measures are thought ahead and primarily include the physical material flow, the information and communication system, and the factory's organizational system. Factory operations, on the other hand, are devoted to the real operation of the equipment and the optimal use of the available resources and framework conditions. The problem and task of permanent over-planning of a factory with its production and logistics structures arises. For this reason, the bidirectional exchange of information and data between factory planning and factory operation can be of great benefit for the optimization of planning and operation. [8], [16]

2.2 Simulation models in cyber-physical production systems

For the areas of factory planning and factory operation, simulation models are mainly used as decision support and are part of the concept of DF. In the technical literature, there are a variety of definition approaches for the term of DF, but essentially this summarizes a comprehensive network of digital models, methods and tools, which are integrated by an end-to-end data management and extend from digital planning to operation. The overarching goal of DF is the holistic planning, evaluation and continuous optimization of all relevant aspects of the real factory. [17]. Further goals of the DF consist in the standardization of planning processes as well as in the reusability of planning models, building blocks and results [18]. An important element of digital factory operation is the support or implementation of end-to-end data management. On the basis of end-to-end data management, for example in the form of model databases, planning results from earlier phases of DF can be used and expanded to include operational data, enabling digital models to be updated and reused [19]. Accordingly, the concept of DF is again fundamental for linking factory planning and factory operation through the transfer of simulation models.

CPPS are of great importance, especially with regard to linking the real world with the virtual world. Here, the production system, which consists of a physical component (e.g., machinery and equipment) and a virtual component (e.g., simulation model), is connected at the center with people in focus. The introduction of CPPS in any production system promises economic, social and even environmental benefits. In general, CPPS can be divided into four main elements - physical world (I), data acquisition (II), virtual world (III), and feedback / control (IV). In the physical world, key performance indicators (KPI) are defined in relation to the task to be performed, which should represent the target for analysis and improvement. Via the important element of (continuous) data acquisition, the measured variables are recorded manually or automatically under appropriate requirements for temporal resolution. The virtual world stands for the model-based production system, the digital image, so to speak. The implementation with suitable computationally processing models, which are e.g. data-based, physical, numerical or agent-based / event-discrete nature, is to be considered here. Finally, the feedback/control element ensures the transformation of the processed data into means for decision-supporting action with human involvement. [20]

In the following, the details of the simulation models used in CPPS are briefly described. Models characterize an abstracted representation of a real system and can be classified in the production system context according to their intended use. The main paradigms in simulation modeling are: System Dynamics (SD), Dynamic Systems (DS), Discrete Event (DE) and Agent Based (AB). Technically, SD and DS are mainly concerned with dynamic system behavior, while DE and AB are mainly concerned with discrete system behavior [21]. In the context of factory planning, the necessary main elements usually have a higher degree of uncertainty and thus a higher degree of abstraction. On the side of the factory operation, there is the demand of an image with a low degree of abstraction towards the consideration of procedural, organizational and structural details. The definition of the objectives with respect to the planning and operational tasks is particularly important in order to be able to select a suitable method for simulation. Discrete process chains (such as material flows) can be analyzed using DE or AB simulation. The state is only changed discretely at certain events. In this case the term production system modeling is used. If the context of the production system is extended by energy flows and the technical building services, a holistic factory modeling is possible using DE, AB and DS, i.e., as shown by SCHÖNEMANN. [22] Of great importance, depending on the planning or operational task and objective, is also the possibility to combine several approaches in one model. The combination of models for all elements of a production system within one simulation would make it possible to analyze dependencies between the system elements involved and the effects of local improvement measures on the overall system [22]. In the context of CPPS and linking planning to operations, real-time simulations of the entire factory can help provide immediate results for short-term decision support in parallel with real production operations [23]. With regard to greenfield and brownfield planning, the main difference is in the input data. While only planning data is available for new planning, it is possible to use real, real-time data from the system for an existing production system.

In order to take into account, the different areas within planning and operation in the production system, the design of AB lends itself. One of the fundamental characteristics of AB is decentralization in modeling and with regard to system behavior. Accordingly, in AB, the system behavior is not defined at a central point, but rather the behavior is defined at an individual level of each agent. Each agent acts accordingly individually according to the logic, behavior and attributes assigned to it. The thus independent, individual resources with specific properties enable a mapping of production, logistics, products, employees and other objects. The system behavior then results from the behavior and interaction of these agents. In addition, agent-based models are considered to be generally easier to maintain and modify, since minor model adjustments result in local rather than global changes. Although all presented simulation paradigms are used in different areas of the factory, DE and AB are probably the most important in the context of simulation in the factory and production context. [5], [21]

3. State of Research

The technical literature provides an enormously high number of publications in the context of factory planning and operation. With the aim to present existing approaches for the simulative coupling of factory planning with factory operation, an extensive literature review of relevant publications in different research areas was conducted. First, approaches for linking factory planning and factory operation in general, where this linking does not have to be specifically supported by simulation use, were considered. Furthermore, the research area with approaches to simulation along the value chain, i.e., with end-to-end simulation and data usage, was reviewed. The focus here is particularly on the simulation of production systems. Finally, approaches were considered that specifically address the topic of cyber-physical production systems in this context. The classification and clustering took place in the following categories:

- ***Thematic focus*:** The relevance of the respective approach for the subject area of factory planning represents the first criterion. Analogously, the reference to factory operation or simulation in the factory context represent the two other criteria in this category.
- ***Methodological approach*:** Here, the approaches regarding the coupling of factory planning and operation, simulation models, and several digital tools were considered.
- ***Simulation application*:** In this category, the contents of the consideration of simulation approaches, model reuse and the integration of a model database were of interest.
- ***Data management*:** Here, the interrelationships were examined from a data technology point of view, to what extent this is done bidirectional, consistent and by means of clearly defined interfaces.

The comparative evaluation in Figure 1 illustrates the large number and variety of concepts for the use of simulation in the context of the factory. The analyzed approaches focus preferably on the design of e.g., framework models for the description of the mutability of production systems for planning purposes (ALBRECHT ET AL.), approaches for modeling and simulation of smart production systems, which aim at achieving interoperability of different simulation components (GORECKI ET AL.) or the detailed consideration of flows in the factory by means of production system modeling (KOMOTO ET AL., GOODALL ET AL.). Few approaches, among them MARTIN ET AL., SCHÖNEMANN ET AL., SIEMON ET AL and ZHENG ET AL. integrate components of holistic factory modeling into their approaches, e.g., by modeling parts of the technical building services. While the advantages of the use of simulation along the value chain, the use of CPPS as well as the linking of factory planning and factory operation became clear, no approach could be identified that fulfills all or nearly all criteria used for the evaluation. The majority fulfillment or at least partial fulfillment of the evaluated sources with regard to the three criteria in the category of thematic focus is countered by the only rare fulfillment of other criteria such as the consideration of several simulation approaches. A methodical approach with regard to the coupling of factory planning and factory operation is also only occasionally part of the evaluated publications. Furthermore, the reuse of models and the integration of a model database is only partially included in the approaches considered. The same applies in particular to the support of bidirectional data management and the detailed consideration of the interface between factory planning and factory operation - both are only very rarely addressed.

	Albrecht et al. (2014)	Dér et al. (2021)	Dombrowski et al. (2019)	Dhungana et al. (2021)	Goodall et al. (2018)	Gorecki et al. (2020)	Horler et al. (2019)	Lachenmaier et al. (2017)	Komoto et al. (2019)	Martin et al. (2021)	Meyer (2014)	Schönemann et al. (2019)	Siemon et al. (2022)	Wagner & Brovkina (2020)	Weyer et al. (2016)	Zhang et al. (2018)	Zheng et al. (2018)
Thematic focus																	
Factory planning	●	●	●	●	○	◕	●	◑	●	●	●	●	●	◕	●	●	◕
Factory operation	◑	◔	●	◑	●	◕	○	●	◔	◕	●	◕	◔	◕	◕	○	◕
Production system modeling	◕	◔	○	○	◑	◑	◑	◕	◑	◕	◔	●	◕	○	◑	◑	◑
Holistic factory modeling	○	○	○	○	○	○	○	○	○	◑	○	●	●	○	◔	○	◔
Methodological approach																	
Methodology for coupling factory planning & operation	◔	◕	●	◑	○	○	○	○	◔	◔	●	◕	○	○	●	○	◑
Methodology for coupling simulation models	◕	○	○	◔	◑	●	●	○	◕	●	◔	●	◕	◔	●	◕	●
Methodology for coupling several digital tools	○	○	◔	●	○	◕	●	◔	●	○	◑	◔	○	●	◔	○	◑
Simulation application																	
Consideration of multiple simulation approaches	●	○	○	○	○	◑	○	○	○	●	○	●	●	○	◕	○	○
Model reuse	○	◔	○	◕	◕	◕	○	◔	●	●	◑	●	○	●	●	●	●
Model database integration	○	○	○	◔	◕	◔	○	○	●	●	◔	●	○	●	●	●	●
Data management																	
Bidirectional	◕	◑	●	◕	◕	◕	◕	◕	◕	◔	●	◔	◕	◕	◕	◕	◕
Consistent	◔	◑	●	●	◑	●	◑	◕	◑	●	●	●	◔	◑	●	◕	◕
Data interfaces	◕	◕	◔	●	●	●	◑	◕	◔	●	◑	●	◔	●	◕	◕	●

○ Not fulfilled criteria ◔ Conditionally fulfilled criteria ◑ Partially fulfilled criteria ◕ Mostly fulfilled criteria ● Completely fulfilled criteria

Figure 1: Overview of the state of research

Thus, the evaluated approaches show a multitude of relevant (partial) aspects regarding the coupling of factory planning and factory operation by the transfer of simulation models within CPPS. Nevertheless, there is a need for further research regarding the topic at hand. For example, there is currently a lack of a methodical procedure in the literature for precisely this linking of factory planning with factory operation with regard to the transfer of simulation models of production systems through CPPS.

4. Method

In the following, the approach for linking factory planning with factory operation by means of AB simulation within the framework of a CPPS is shown (cf. Figure 2). Before the framework can be initialized, the preparation and rough planning steps must already be run through in the planning process, so that the approach can be followed from the detailed planning onwards. Based on a normal CPPS, the framework was structured in this case on the side of the real and cyber world into three different layers that build on each other. The cycles running through are to be understood in each case in the arrangements [I-IV], [1-4] as well as [A-D].

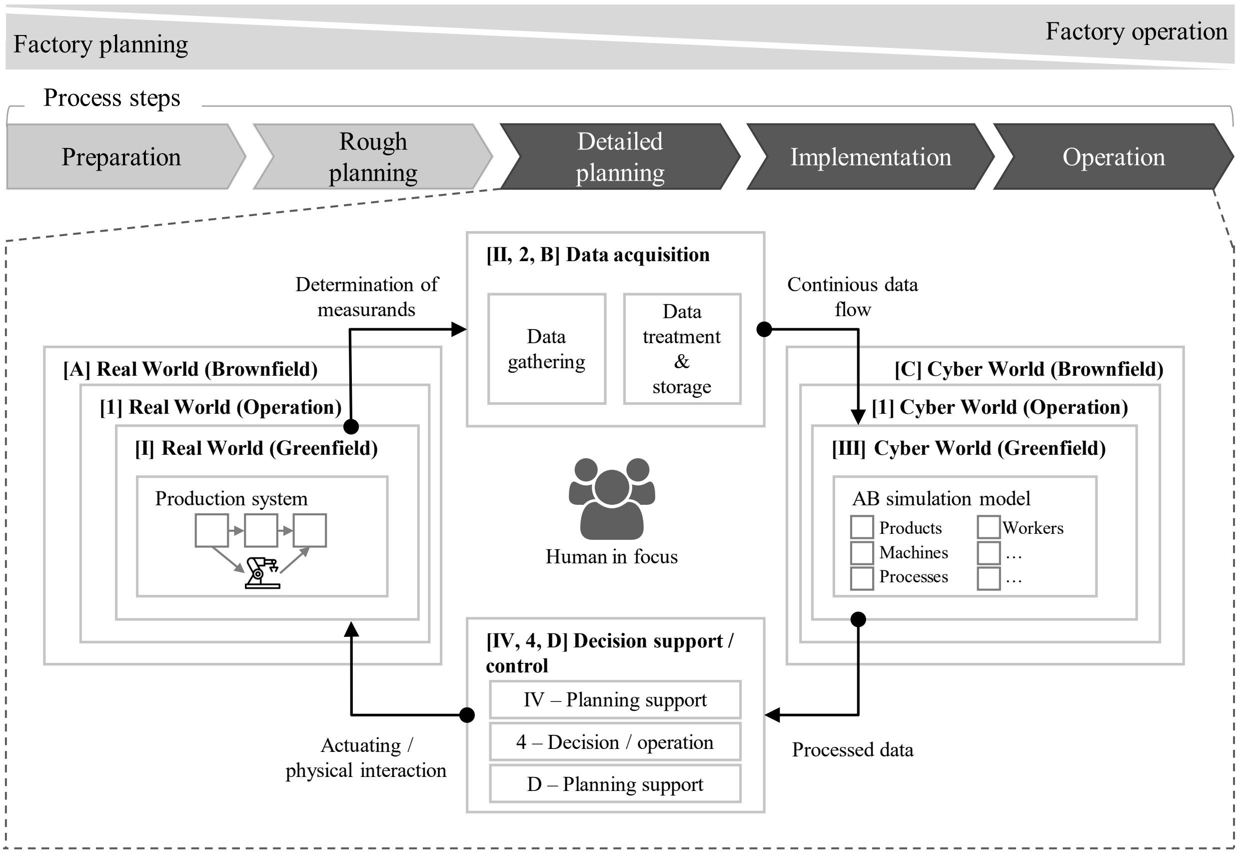

Figure 2: Framework for linking factory planning and operation using AB simulation in the context of a CPPS

- Cycle [I] to [IV]:

This cycle marks the starting point in the application of the framework. Starting from the greenfield planning, the factory planning process takes place in the real world with respect to the design of the production system. Manually, by means of data acquisition, the planning data is collected and transferred to the AB Greenfield simulation model on the cyber side. This model accesses a comprehensive network of agents (such as products, machines, processes, etc.). Based on the planning data, an evaluation of the planning scenarios can be performed. This planning support is transferred to the real world by the human being, who is the central focus, and can thus be used for adjustments in the planning process. The inner cycle is still primarily based on expert estimates and aims at initializing the AB simulation model.

- Cycle [1] to [4]:

After the ramp-up of the production system, the first data acquisition of real-time data is used to establish a quasi-real-time connection between the real and virtual worlds. Here, the agents in the specific executions are provided with the data as input (real / operational data) and thus a mapping and prognosis of the production system can take place. The goal here is the decision support in the operation execution as well as the control and regulation of the production system.

- Cycle [A] to [D]:

The outermost cycle describes the case of brownfield changes. In this concrete planning procedure, changes are to be made to the production system based on the real world. This is where the benefit of continuing to use the simulation model comes into play. A new development is omitted, instead the agents for the respective area (e.g., product) are initialized with a data mix as input. Thus, on the one hand, planning data for the desired changes and real / operational data from the current production system are combined. In this way, important knowledge for detailed planning can be transferred between planning and operation and, conversely, planning support can be designed specifically for the real operation of the production system.

5. Conclusion and outlook

This paper has shown a conceptual approach in the context of the interface between factory planning and operation, how a CPPS can be initialized starting from greenfield planning. Initially, the simulation models are developed on the virtual world side on the basis of plan data, which are acquired manually. In addition, the targets have to be transferred to the generic modules of the AB in the form of planning variables. From this, first simulation runs can be realized and planning scenarios can be evaluated. If the planning is far advanced and the commissioning of the factory elements has taken place, real data of the factory operation can be accessed in the next step and the data acquisition can be carried out via an automated interface. The simulation model, adapted to real operation, can now be used in quasi real-time and supports the operation and control of the production system in the factory. In the last extension step, both sides of factory planning and factory operation can access the virtual world and simulatively evaluate brownfield changes by the combination of plan and real data. Particularly noteworthy at this point is the generic initialization of the AB, so that the simulation modules can be provided with plan or real data. Based on the Greenfield planning approach, the necessary steps for the preparation of a real-time capable CPPS can be taken. In the further course, the interdisciplinary departments can equally bring about forms of decision support by preparing the virtual world for the issues to be solved by simulation in terms of data technology.

In the future, this generic framework can be used and extended. In particular, the focus on an ecologically sustainable design of factory systems could again extend the approach by building blocks of the technical building equipment as well as the factory shell. In addition, the use of the framework is limited to the results from the rough planning, since e.g., changes to the layout etc. are not processed by the simulation model. Further research should be carried out in this interface, since the increase in the degrees of freedom in an early planning phase greatly increases the demands on the simulation models.

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